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New Heat and Cold Strain Predictive Indices*

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Summary

New heat and cold strain predictive indices have recently been developed which should be of great military utility. The physiological strain index (PSI), based on rectal temperature (T_{re}) and heart rate (HR), is capable of indicating heat strain online and analyzing existing databases. We assumed that the maximal T_{re} and HR rise during exposure to exercise-heat stress from normothermia to hyperthermia was 3°C (36.5°C to 39.5°C) and 120 beats/min (60 to 180 beats/min), respectively. T_{re} and HR were assigned the same weight functions as follows:

$$PSI=5(T_{ret}-T_{re0})\cdot(39.5-T_{re0})^{-1}+5(HR_t-HR_0)\cdot(180-HR_0)^{-1}$$

where T_{ret} and HR_t are simultaneous measurements taken at any time during the exposure and T_{re0} and HR_0 are the initial measurements. Six independent studies, containing eight different databases were analyzed in order to evaluate PSI for different climatic conditions, hydration levels, types of clothing, exercise intensities, gender and the effects of aging. PSI was capable of significantly differentiating ($P < 0.05$) between all of these conditions and some combinations of these conditions. Our cold strain index (CSI), based on core (T_{core}) and mean skin temperatures ($\overline{T}_{sk}$), is capable of indicating cold strain in real time and analyzing existing databases. T_{core} represents both T_{re} and esophageal temperature (T_{es}). CSI was calculated as follows:

$$CSI=6.67(T_{coret}-T_{core0})\cdot(35-T_{core0})^{-1}+3.33(\overline{T}_{skt}-\overline{T}_{sk0})\cdot(20-\overline{T}_{sk0})^{-1}$$

where T_{core0} and $\overline{T}_{sk0}$ are the initial measurements and T_{coret} and $\overline{T}_{skt}$ are simultaneous measurements taken at any time during the exposure; when $T_{coret} > T_{core0}$, then $T_{coret} - T_{core0} = 0$. Three independent studies containing three different databases were analyzed in order to evaluate CSI for different cold air and cold-water immersion conditions. CSI significantly differentiated ($P < 0.01$) between the conditions for two of these three databases. However, further study is required to possibly adjust CSI for a wider range of cold air and water temperatures, and to consider the effects of physical exercise. Both PSI and CSI rate heat and cold strain on a universal scale of 0-10. Both indices have the potential to be widely accepted and used universally for many military scenarios.

*LTC Daniel S. Moran, Ph.D. developed these new heat and cold strain predictive indices while working at the U.S. Army Research Institute of Environmental Medicine as a National Research Council Fellow.

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Introduction

Over the last century, scientists have attempted to combine environmental parameters and physiological responses to develop a variety of heat stress/strain indices. The existing indices can be divided into two main categories: effective temperature indices that are derived from climatic parameters only (i.e., ambient temperature, wet-bulb temperature, and/or black-globe temperature, etc.), and rational heat indices which incorporate a combination of climatic and physiological parameters (i.e., radiative and convective heat transfer, evaporative capacity of the environment, and/or metabolic heat production, etc.). Although more than 20 heat strain indices have already been developed, none are universally accepted as the physiological strain index with regard to exercise-heat stress. Some of the main reasons for lack of universal acceptance involve a combination of potential problems including the complexity of calculation, the lack of a universal scale, inability to make calculations online, the limited applicability of some indices for diverse climatic conditions, and assumed corrections for protective clothing and different metabolic rates. In 1980, Lee (4) concluded that “Any reader who was hoping for the evolution of a single heat index applicable to all aspects of human endeavor must by now be sadly disappointed”.

Over the last half century, researchers have also attempted to derive a number of different cold stress/strain indices. Less than 10 cold strain indices currently exist, and most of these are based on ambient temperature and wind chill. The most notable is probably that developed by Siple and Passel (18) which is referred to as the wind chill index. This index utilizes the cooling power of the environment by integrating the effects of ambient temperature and wind velocity to assess the convective cooling power. However, wind chill and ambient temperature merely quantify the stress to the unprotected body surface area. Also, the wind chill index is applicable only at wind speeds exceeding 20 m/s, overestimates the cooling power of a nude person, and underestimates the cooling power for a clothed person (8).

The most commonly accepted physiological criterion of heat strain was best defined in 1905 by Haldane (3) as the inability to maintain body core temperature at the level prescribed by the thermoregulatory center. In addition, core temperature has generally been accepted as an appropriate physiological measure for assessing cold strain, and also involved in the categorization of different stages of hypothermia. Therefore, core temperature was assumed to be essential in the development of new physiologically-based indices of heat and cold strain, and the primary thermoregulatory input to these indices. Heart rate (HR) was thought to be an appropriate physiological measure of the cardiovascular strain associated with exercise-heat stress and useful for heat strain index development. Since mean skin temperature ($\bar{T}_{sk}$) was found to be rapidly affected by cold exposure, we assumed that this measure could be used to reflect changes in ongoing dynamic heat exchange and useful for cold strain index development.

This report summarizes the development of our new physiological strain index (PSI) which is based on rectal (T_{re}) or in some cases esophageal (T_{es}) temperature and HR (13). PSI has been shown to effectively differentiate the heat strain associated with different climatic conditions, hydration levels, types of clothing including protective clothing, different exercise intensities, gender, and the effects of aging (10, 11, 12, 13, 14, 15). Our new cold strain index (CSI) is based on core temperature (T_{re} or T_{es}) and $\bar{T}_{sk}$ (8). CSI has been demonstrated to be effective in depicting cold strain for both cold air and cold-water immersion primarily during resting conditions (8). While no significant refinements to PSI appear necessary, CSI may need to be further adjusted to consider a wider range of cold air and water temperatures, and to better consider the effects of physical exercise (2, 8).

PSI and CSI Development/Validation

The new PSI was developed/validated from two different databases collected from subjects who differed in their aerobic fitness and heat tolerance. One of these databases served to develop PSI while the second database from an independent study was used to validate PSI. A detailed description of the development/validation of PSI can be found in a paper published by Moran and colleagues (13); however, a brief description of the approaches taken will be presented.

One hundred healthy young men at different levels of aerobic fitness and heat acclimation volunteered to participate in the study used to develop PSI. The physical characteristics of these men were (mean±SE): age, 20±3 yr; height, 178±10 cm; weight, 74.6±10.5 kg; and, body surface area, 1.92±0.15 m^2. All of these young men were informed as to the nature of the study, potential risks of exposure to exercise in a hot climate, and signed a consent form. These men wore shorts and sport shoes while walking at 1.34 m/s (2% grade) in a hot/dry climate of 40ºC, 40% relative humidity (RH) for 120 min. T_{re} and HR were continuously monitored and recorded at 1 min intervals. Several experiments were terminated when a subject voluntarily withdrew or reached a T_{re} of 39ºC and/or HR exceeded 180 beats/min.

PSI was calculated as follows:

$$PSI=5(T_{ret}-T_{re0})\cdot(39.5-T_{re0})^{-1}+5(HR_t-HR_0)\cdot(180-HR_0)^{-1}$$

where T_{ret} and HR_t are simultaneous measurements taken at any time during the exposure and T_{re0} and HR_0 are the initial measurements. T_{re} and HR which depicts the combined load of the thermoregulatory and cardiovascular systems were assigned the same weight by using a constant of 5. Thus, PSI was scaled to a range of 0-10 within the limits of the following values: $36.5\leq T_{re}\leq 39.5$ºC and $60\leq HR\leq 180$ beats/min.

Table 1. Calculated PSI from measured HR and T_{re} obtained from 100 young men exposed to 120 min exercise-heat stress

Strain	PSI	HR, beats/min	T_{re}, ºC	*n*
	0	71±1.0	37.12±0.03	100
No/little	1	90±1.1	37.15±0.04	47
	2	103±1.1	37.35±0.03	81
Low	3	115±1.3	37.61±0.03	80
	4	125±1.4	37.77±0.04	61
Moderate	5	140±1.9	37.99±0.05	28
	6	145±5.3	38.27±0.07	13
High	7	159±1.3	38.60±0.04	5
	8	175	38.7	1
Very high	9			0
	10			0

Values are means±SE (*n* is number of subjects). Heat stress, 40°C, 40% RH, walking 1.34 m/s at 2% grade. No data available for very high strain. From reference 13.

Table 1 depicts the newly-developed PSI applied to the data obtained from the 100 young men performing exercise in the heat. Because these men were not a homogeneous group and varied in their aerobic fitness, heat acclimation status and tolerance to exercise-heat stress, data analysis was applied individually.

The new CSI constructed to evaluate the impact of cold stress used the same basic concepts involved with PSI. Because $\overline{T}_{sk}$ changes very quickly in response to cold environments and T_{core} (T_{re} or T_{es}) reflects the thermoregulatory strain, we decided that these two parameters should adequately depict the cold strain resulting from either cold air or cold-water immersion. The weighting constants for these two physiological parameters were similar to that described for mean body temperature or 6.67 for T_{core} and 3.33 for $\overline{T}_{sk}$. CSI was scaled to a range of 0-10 within the limits of the following values: $35 \leq T_{core} \leq 38$°C and $20 \leq \overline{T}_{sk} \leq 35$°C. Therefore, CSI was calculated as follows:

$$CSI = 6.67(T_{coret} - T_{core0}) \cdot (35 - T_{core0})^{-1} + 3.33(\overline{T}_{skt} - \overline{T}_{sk0}) \cdot (20 - \overline{T}_{sk0})^{-1}$$

where T_{core0} and $\overline{T}_{sk0}$ are the initial measurements and T_{coret} and $\overline{T}_{skt}$ are simultaneous measurements taken at any time during the exposure; when $T_{coret} > T_{core0}$, then $T_{coret} - T_{core0} = 0$. Three different databases were analyzed in order to evaluate CSI for different cold air and cold-water immersion conditions during rest.

Table 2. Evaluation and categorization of different heat and cold strains by PSI and CSI, respectively

Strain	PSI/CSI
No/little	**0**
	1
	2
Low	**3**
	4
Moderate	**5**
	6
High	**7**
	8
Very high	**9**
	10

From reference 12.

Table 2 illustrates the heat and cold strain verbal categorizations associated with the numerical values for PSI and CSI. This universal scale from 0-10 was originally derived for PSI but has also been found to be applicable to CSI.

Results and Discussion

Physiological Strain Index. Six independent studies, containing eight different databases were analyzed in order to evaluate PSI for different climatic conditions, types of clothing including protective clothing, exercise intensities, hydration levels, gender and aging. In the first study, Montain and colleagues (7) studied seven young men wearing full (clo=1.5) or partial (clo=1.3) protective clothing who performed light exercise for 180 min in either hot/dry or hot/wet climatic conditions (43°C, 20% RH; 35°C, 50%RH, respectively). As shown in Figure 1, PSI significantly differentiated ($P < 0.05$) between the heat strain in the hot/dry and hot/wet climates, and also between the full (MOPP IV) and the partial (MOPP I) protective clothing configurations.

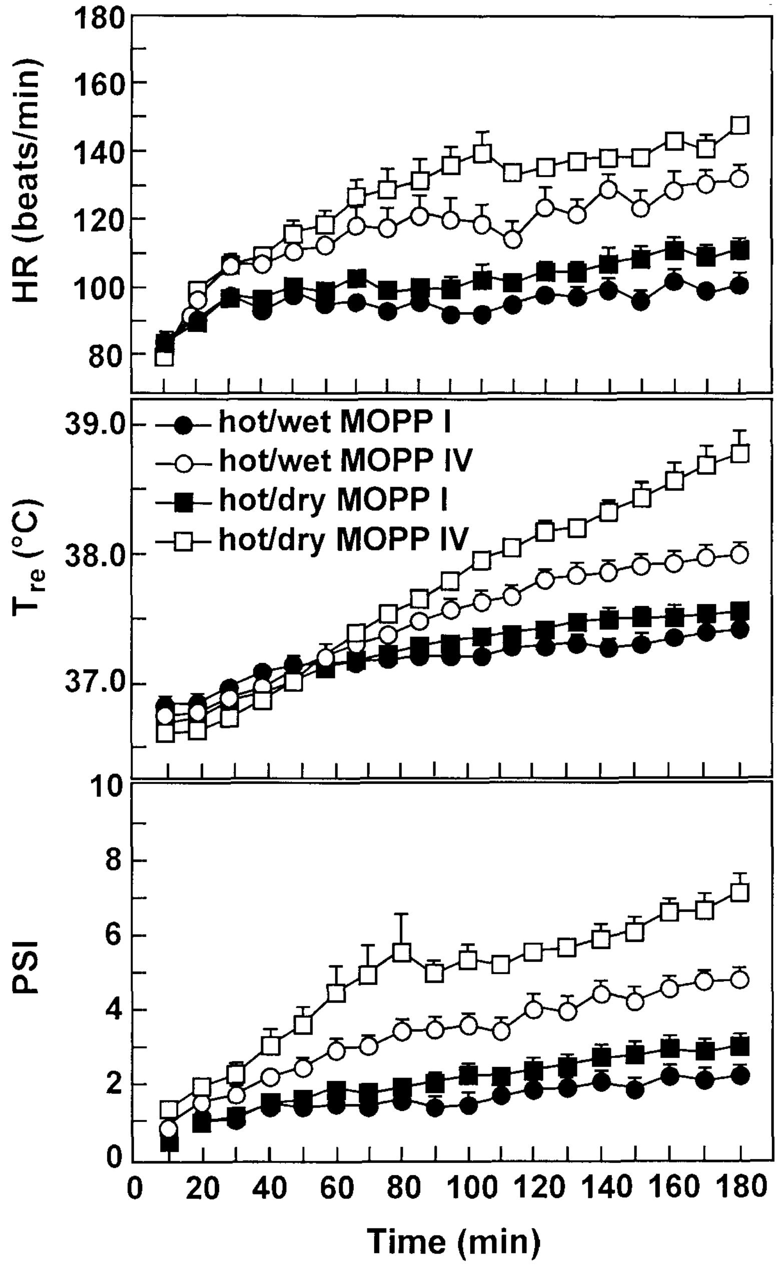

Figure 1. Comparison between HR (top), T_{re} (middle) and PSI (bottom) in hot-dry and hot-wet climates wearing partial (MOPP I) and full (MOPP IV) protective clothing. From reference 15.

Evaluation of PSI for different levels of dehydration during prolonged exercise was completed using a database from Montain and Coyle (5) within the range of HR=55-175 beats/min, T_{re}=36.8-39.7°C and T_{es}=36.4-39.2°C. Eight endurance-trained male cyclists (age, 23±3 yr; weight, 72.2±11.6 kg; $\dot{V}O_2max$, 66.2±7.6 $ml \bullet kg^{-1} \bullet min^{-1}$) cycled at a power output eliciting 62-67% $\dot{V}O_2max$ for 120 min in a warm climate (33°C, 50% RH). Each man completed four experimental exposures while ingesting different volumes of fluid during exercise: no fluid, or a volume that replaced 20%, 50% or 80% of the fluid lost in sweating resulting in 4.2%±0.1, 3.4%±0.1, 2.3%±0.1, or 1.1%±0.1 body weight loss (BWL), respectively after 120 min cycling. Figure 2 shows that T_{re} was generally elevated in proportion to the magnitude of the hypohydration levels and the four trials were significantly different from each other ($P < 0.05$) with the exception of the 3.4% and 4.2% BWL exposures. HR increased progressively during exercise at the different hypohydration levels; however, HR at 120 min of exercise was not significantly different between the exposures of 1.1% and 2.3% BWL, and the 3.4% and 4.2% BWL. Figure 2 illustrates PSI correctly discriminated between the four different hypohydration levels at this exercise intensity.

Montain and colleagues (6) studied nine young acclimated men (age, 24±2 yr; height, 176±3 cm; weight, 81.7±4.5 kg; $\dot{V}O_2max$, 57±2 $ml \bullet kg^{-1} \bullet min^{-1}$) who completed nine 50 min exercise exposures in a warm climate (30°C, 50% RH). These exposures consisted of treadmill exercise at three intensities: 25, 45 and 65% $\dot{V}O_2max$ when either euhydrated or hypohydrated by 3 and 5% of each subjects' baseline body weight. Table 3 shows that PSI correctly categorized the heat strain in rank order to the various combinations of exercise intensity and hydration level. The euhydration exposures were generally ranked as little or low strain with values of 1.6±0.2 to 3.1±0.3. The 3% BWL exposures were ranked as moderate strain and ranged from 4.3±0.2 to 6.4±0.4 while the 5% BWL exposures were categorized with high or very high strain ranging from 7.4±0.3 to 10.0±0.9.

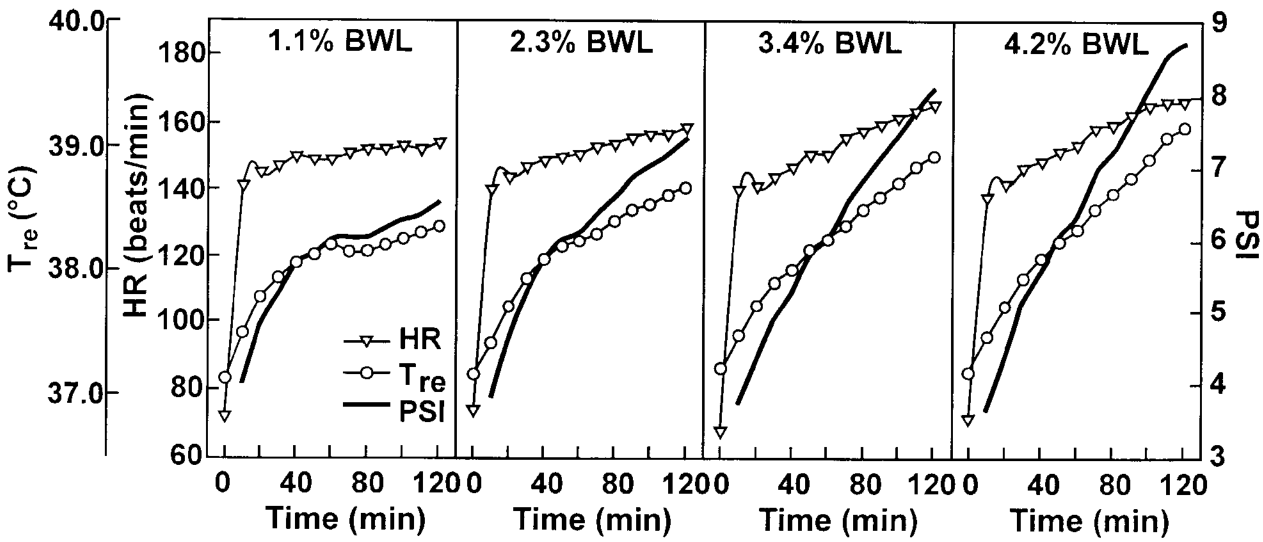

Figure 2. The PSI calculated from T_{re} and HR applied to mean values obtained from men exposed to exercise-heat stress at 4 different levels of hypohydration. From reference 11.

Table 3. Calculated PSI depicting the effects of work intensity and/or hydration level

Work Intensity, % $\dot{V}O_2max$	**Hydration, %BWL**	**PSI Units**	**PSI Strain**
25	**0**	**1.6±0.2**	**Little**
	3	**2.2±0.3**	**Little**
	5	**3.1±0.3**	**Low**
45	**0**	**4.3±0.2**	**Low**
	3	**5.5±0.4**	**Moderate**
	5	**6.4±0.4**	**Moderate**
65	**0**	**7.4±0.3**	**High**
	3	**9.1±0.9**	**Very high**
	5	**10.0±0.9**	**Very high**

Unit values are means±SE. Nine men performed 50 min exercise in the heat (30°C, 50% RH) at different exercise intensities (25, 45 and 65% $\dot{V}O_2max$) and different hydration levels (euhydration and hypohydration at 3 and 5% body weight). From reference 11.

Moran and colleagues (12) also evaluated PSI for gender differences under various combinations of exercise intensity and climate. Two groups of eight men each were formed according to $\dot{V}O_2max$ where the first group of men (M) was matched to a group of nine women (W) with similar ($P > 0.001$) $\dot{V}O_2max$ (46.1±2.0 and 43.6±2.9 $ml \bullet kg^{-1} \bullet min^{-1}$, respectively). The second group of men (FM) was significantly ($P < 0.001$) more aerobically fit than M or W with $\dot{V}O_2max$ of 59.1±1.8 $ml \bullet kg^{-1} \bullet min^{-1}$. No significant differences ($P < 0.05$) existed between these three groups for age, weight, height and body mass index. Therefore, the relative exercise intensity (% $\dot{V}O_2max$) during these experiments was the same for M and W but significantly lower for FM. Subjects completed a matrix of nine experimental combinations consisting of three different exercise intensities for 60 min [low, moderate and high (300, 500 and 650 W, respectively)] each at three different climates [comfortable, hot wet and hot dry (20°C, 50%RH; 35°C, 70%RH; and 40°C, 35%RH)].

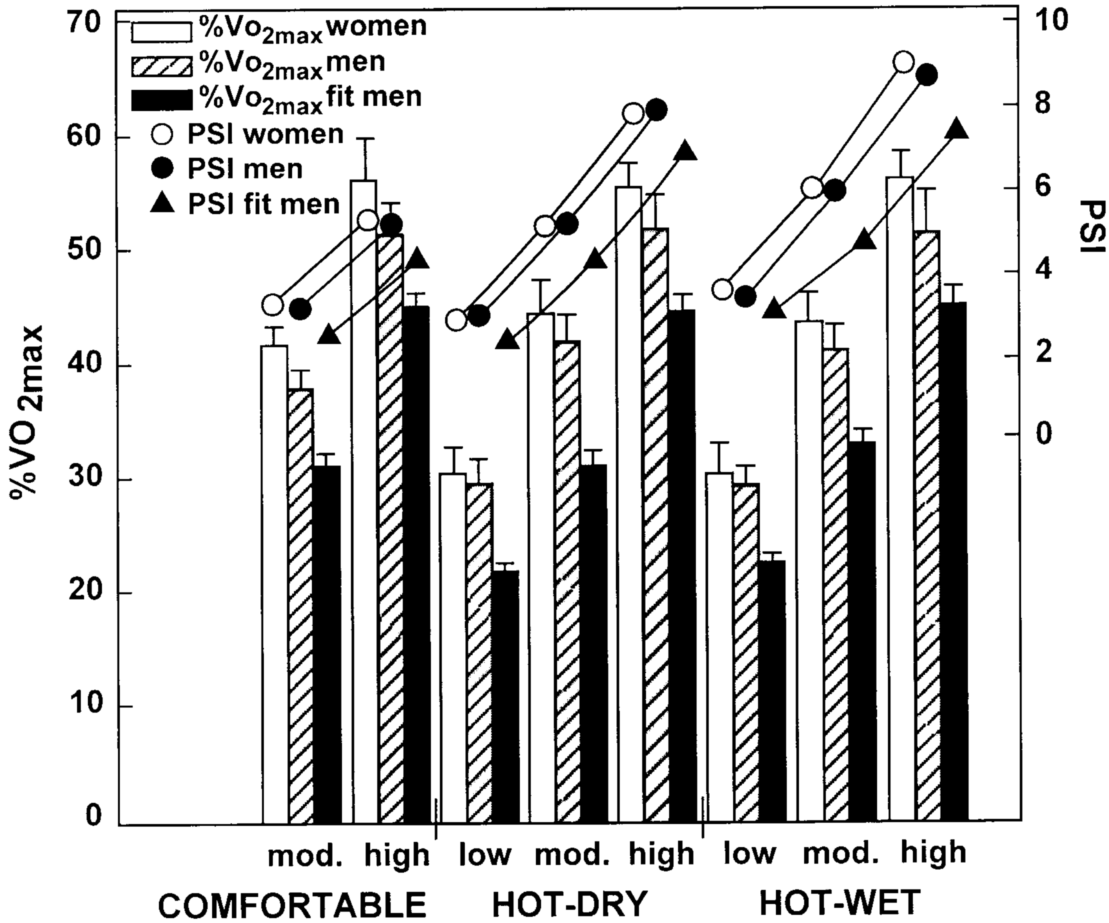

Figure 3. PSI and relative $\dot{V}O_2max$ (mean±SE) after 60 min for the three groups of men (men=M and fit men=FM) and women (women=W) during the various combinations of exercise intensity and climate. From reference 12.

The relative $\dot{V}O_2max$ and simultaneously calculated PSI are depicted in Figure 3. Generally, significant differences ($P < 0.01$) were found in $\%\dot{V}O_2max$ between the different exercise intensities. However, no significant differences ($P > 0.05$) were found between the same exercise intensities for the different climatic conditions. In all experimental exposures, the lowest $\%\dot{V}O_2max$ values were calculated for FM and found to be significantly different ($P < 0.05$) from W or M. No significant differences were found in $\%\dot{V}O_2max$ between W and M. High correlations were found between $\%\dot{V}O_2max$ and PSI in two different statistical analyses. First, for the different exercise intensities under the same climatic conditions (r=0.99), and second, when compared between the different groups for the same exercise intensity and climatic condition (r=0.96).

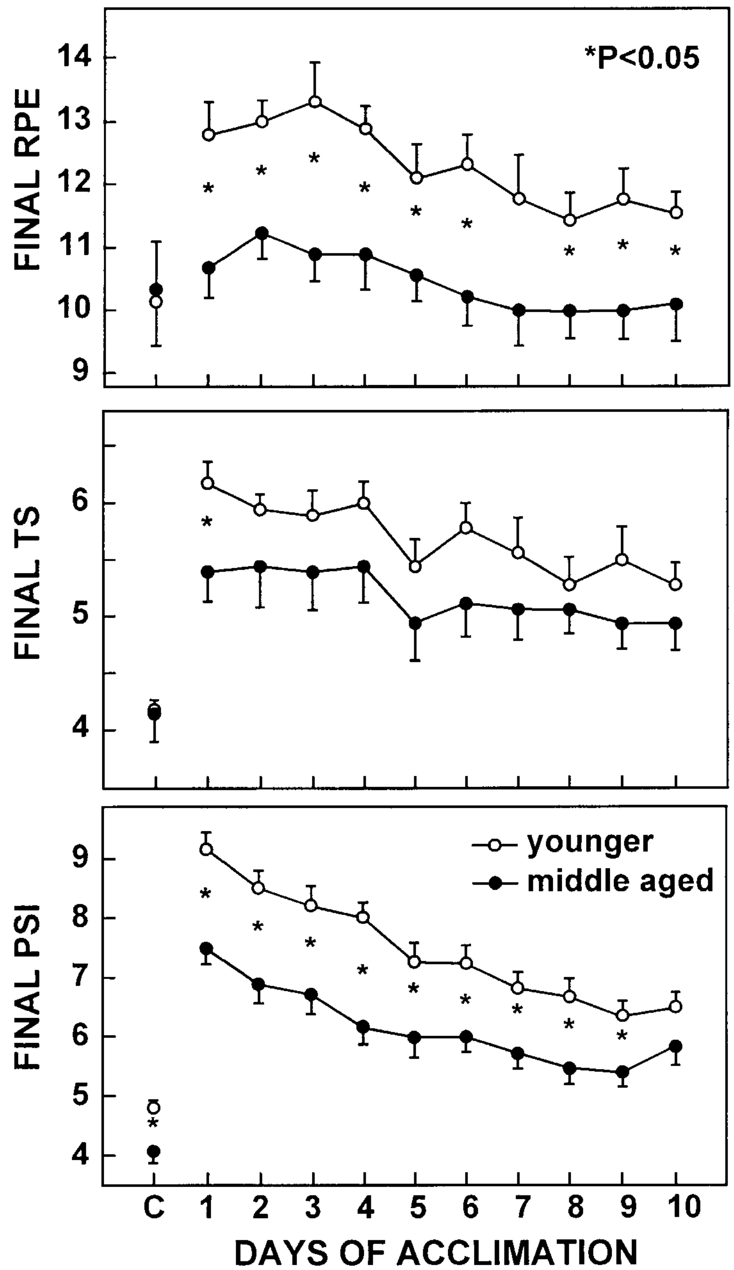

Figure 4. Mean (±SE) final rated perceived exertion (RPE), thermal sensation (TS) and PSI of 9 young and 9 middle-aged men during the control (C) day and each of 10 exercise-heat acclimation days. From reference 10.

Evaluation of PSI for young (21±1 yr) and middle-aged (46±2 yr) men during 10 days of exercise-heat acclimation was conducted using a database from Pandolf and colleagues (17). Two groups of 9 men each were matched ($P > 0.05$) for $\dot{V}O_2max$ (52.9±1.7 and 51.3±3.1 $ml \bullet kg^{-1} \bullet min^{-1}$, young and middle-aged, respectively) and physical characteristics (weight, 76.3±2.2 and 82.2±3.2 kg; surface area, 1.90±0.03 and 2.01±0.04 m^2 for the same two groups, respectively). Subjects were heat acclimated for 120 min by treadmill walking (1.56 m/s, 5% grade) for 10 consecutive days in a hot-dry (49°C, 20% RH) climate. The exercise intensity required ~45% $\dot{V}O_2max$ for both groups.

Heat acclimation was preceded by an identical protocol in a comfortable climate (22°C, 50% RH). Although not shown, final T_{re} and HR decreased ($P < 0.05$) for both groups from the first to last acclimation day (17). Final T_{re} was higher ($P < 0.05$) for the young men during each of the first 4 acclimation days and displayed a trend ($P > 0.05$) to be higher on the remaining acclimation days while final HR was higher ($P < 0.05$) for the young men on days 1, 2, 4, 5 and 7 of acclimation and also showed a trend ($P > 0.05$) to be higher on the other acclimation days (17). Rated perceived exertion (RPE, 1) and thermal sensation (TS, 19) were also measured during these experiments. Figure 4 shows that final values for RPE, TS and PSI all had higher strain for the younger compared to the middle-aged men throughout the 10-day acclimation. Significant differences ($P < 0.05$) for RPE were found on all acclimation days except day 7, whereas, for TS significant differences were noted only on day 1. PSI was higher ($P < 0.05$) for the younger men on days 1-9. Thus, PSI not only reflected the T_{re} and HR responses between these two groups during acclimation but also showed a strong relationship with the perceptual responses from these experiments (12).

Cold Strain Index. Three independent studies involving three different databases were analyzed in order to develop and evaluate CSI for different cold air and cold-water immersion conditions (8). CSI seemed to adequately describe the resultant cold strain during rest but might need to be adjusted to consider the effects of physical exercise.

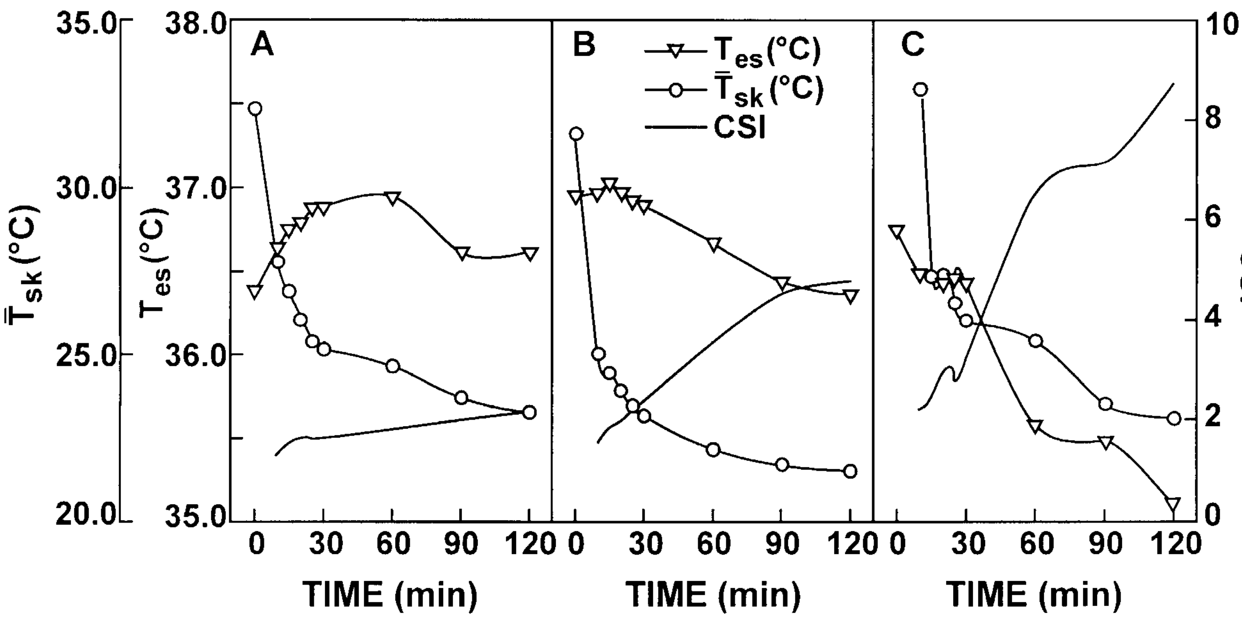

Figure 5. Cold strain index (CSI) calculated from esophageal temperature (T_{es}) and mean skin temperature ($\bar{T}_{sk}$) applied to three young men exposed to the same cold-air stress (7°C, 40% RH; data from reference 16). A, B and C refer to subjects 1, 2 and 3, respectively. From reference 8.

Nine young men participated in a study published by O'Brien and colleagues (16) which was used to develop the new CSI. The physical characteristics of these men were (mean±SE): age, 24±2 yr; height, 178±2 cm; weight, 77±4 kg; and $\dot{V}O_2max$, 55±1 $ml \bullet kg^{-1} \bullet min^{-1}$. These men were dressed in shorts, socks and shoes during the experimental trials which consisted of 30 min of rest in comfortable climatic conditions (25°C) followed by 120 min of rest in cold air (7°C, 40% RH). Because these men were not a homogeneous group and cold exposure resulted in large individual differences in physiological responses, data were analyzed individually (8).

Figure 5 depicts the data obtained from O'Brien and colleagues (16) on three different subjects exposed to the same cold-air conditions at the same hydration state but at different cold-strain levels during these cold exposures. Little cold strain, rated by CSI as 2, was observed for subject A; low-to-moderate strain which gradually increased and after 120 min reached 4.8 was seen for subject B; and, high cold strain which almost linearly increased with exposure time and ended as 8.7 was seen for subject C (8).

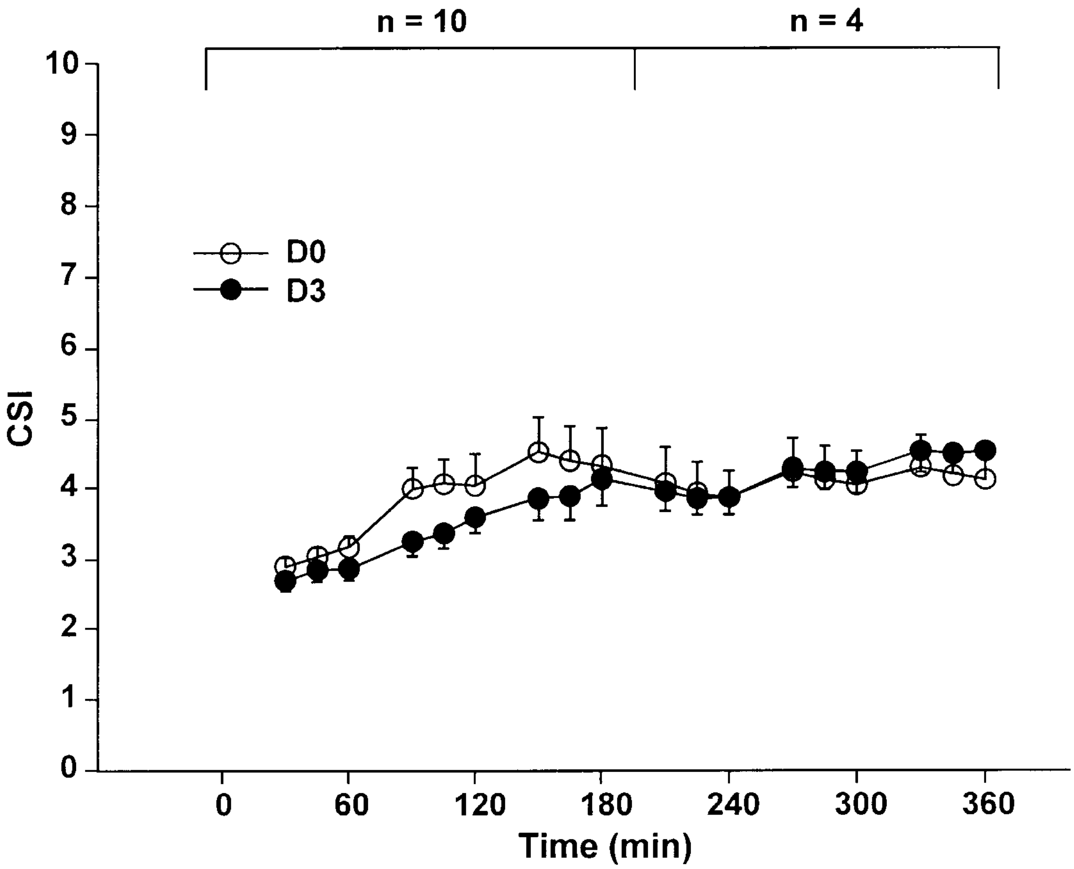

Figure 6. Cold strain index (CSI) versus time during exercise-cold exposure before and after 3 days of exhaustive exercise. Data from 0 to 180 min from n=10 men, data from 190 to 360 min from n=4 men. From reference 2.

In a recent study, Castellani and colleagues (2) evaluated 10 young men (mean ±SE: age, 24±1 yr; height, 177±2 cm; weight, 82.8±3.6 kg; %fat, 16.4±1.9%; $\dot{V}O_2$peak, 56.0±1.8 $ml \bullet kg^{-1} \bullet min^{-1}$; and, body surface area, 1.99±0.05 m^2) who exercised in cold-wet conditions for 6 hr before (D0) and after 3 days of exhaustive exercise (D3). Each hour of the cold-wet conditions consisted of 10 min standing in rain (5.4 cm/hr, 5°C air) followed by 45 min treadmill walking (1.34 m/s, 5.4 m/s wind, 5°C air). Although not shown, the change in T_{re} across time was greater ($P < 0.05$) for D3 versus D0, and the change in $\overline{T}_{sk}$ was less ($P < 0.05$) for D3 versus D0. Figure 6 shows the corresponding CSI responses for these same experiments. Although CSI increased across time, the index at the end of both trials (D3=4.6±0.6, D0=4.2±0.8) was similar ($P > 0.05$). Thus, although $\overline{T}_{sk}$ was 1.3°C higher ($P < 0.05$) and T_{re} was 0.3°C lower ($P < 0.05$) on D3 versus D0, CSI could not discriminate the greater heat loss that occurred on D3. These findings would seem to indicate that when vasoconstrictor responses to cold are altered such as following exhaustive exercise, CSI may not adequately quantify the associated cold strain.

Conclusions

PSI has been shown to adequately reflect the associated heat strain for different climatic conditions, types of clothing including protective clothing, various hydration levels, different exercise intensities, gender, and the effects of aging. In addition, adjusted PSI can discriminate the heat strain in non-human species such as rats during exercise-heat stress (9). Thus, PSI does not seem to require any significant refinements. CSI has been shown to be effective in depicting cold strain for both cold air and cold-water immersion during resting conditions. However, CSI may need to be further adjusted to better consider the effects of physical exercise, and also a wider range of cold air and water temperatures. We speculate that the addition of HR to CSI as a third component to this index could potentially be the proper adjustment. Nevertheless, both indices have the potential to be widely accepted and used universally for many military scenarios.

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